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## What darkens the Greenland ice sheet?

By [M. Tedesco](#) and others

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Most of the massive ice sheet that covers roughly four-fifths of Greenland melts at the surface in summer. As long as the ice sheet regains its mass in the winter, this is not catastrophic. But if the ice sheet melted entirely, sea levels would rise by more than seven meters, with obvious and severe consequences for human civilization.

Not surprisingly, scientists are working hard to determine if and when the ice sheet will transition (or if it has already transitioned) from a stable state to a net mass loss state. What the impact of increasing greenhouse gas levels is on the Greenland ice sheet (GrIS) depends on many complex and interacting factors.

One is the ice sheet's albedo—the fraction of incoming solar radiation that is reflected from the ice sheet surface. Indeed, scientists have determined that net solar radiation reaching the ice is the largest contributor to the energy balance driving melting (e.g., van den Broeke et al., 2011). Despite its importance, we have yet to quantify the role of the different processes affecting albedo over the GrIS albedo. Such an understanding is crucial to determining the past behavior of the GrIS and projecting its future contribution to sea-level rise.

Scientists seeking to quantify how much various factors contribute to ice sheet albedo face numerous challenges. These include intrinsic limitations in current observational capabilities (e.g., spatial and radiometric resolution of currently available spaceborne sensors) and limitations in how accurately surface energy balance models handle ice sheet albedo. Moreover, the sparseness in space and time of *in-situ* observations of quantities such as impurity concentrations, biological processes and grain growth impedes our ability to separate their respective contributions to broadband albedo.

## **Darkening: a complex suite of processes**

The GrIS albedo has declined substantially in recent decades (Tedesco et al., 2014), attracting interest from both the scientific community and news media. Media reports, many using the term “darkening”, have emphasized that an increase in light-absorbing impurities, particularly black carbon and dust, in Greenland snow could be responsible for the observed albedo reduction. The idea is that such impurities absorb incoming sunlight, heating up and accelerating snow and ice melt. Surface impurities can indeed reduce albedo in the visible part of the electromagnetic spectrum—light with wavelengths from 400 to 700 nanometers—and make snow and ice appear darker to our eyes. Visual images of “dirty” snow or ice are therefore appealing as a source of snow darkening and can be powerful communication tools.

However, half the solar energy Earth receives is at near-infrared wavelengths (between 700 and 2500 nanometers), which is invisible to our eyes. At these wavelengths, other powerful means of albedo reduction become important. Hence, a comprehensive assessment of GrIS darkening must account for all processes that contribute to albedo reduction. Important factors include snow grain size, the impurity content of snow, biological activity, exposure of bare ice, formation of melt pools, and the combined effects and feedbacks associated with all of these factors.

We briefly discuss these processes below. We assert that each is potentially significant enough that the scientific community must quantify its role in GrIS darkening. Because each process responds positively to warming (i.e., albedo decreases as warming increases), they are all likely to become increasingly important in the future.

## **Snow grains growth: an invisible effect on albedo**

Soon after snow falls, its grains begin to change shape and size. Snow grains become rounded, and large grains grow at the expense of small grains, so the average grain radius increases with snowpack age.

At near-infrared wavelengths, coarse-grained snow has lower albedo than fine-grained snow. Warming accelerates this snow aging process, leading to further albedo reduction. In melting snow, grains become further rounded and clump into clusters. Thus, there is a positive feedback between warming, snow aging, increased solar absorption and reduced albedo.

Since the reduction of albedo by grain growth is confined to the near-infrared, it is mostly invisible to our eyes. This means that a clean snowpack (i.e., one with no impurities) that has melted at the surface can have a lower broadband albedo (e.g., integrated over the entire spectrum) than a cold snowpack with impurities, despite the fact that the clean snowpack might still appear brighter to our eyes.

For pure snow, grain growth from new snow (with radius around 0.1 millimeters) to old melting snow (radius around 1 mm) can reduce broadband albedo by around 10%. By comparison, adding 20 parts per billion of black carbon, a concentration typical of those scientists have found in the top layer of melting GrIS snow in the percolation zone, reduces albedo by only one to two percent.

### **Dirt on the surface**

Light-absorbing impurities such as black carbon, organic carbon and dust are deposited on the GrIS from the atmosphere. Over most of the central GrIS, however, the impurity content in cold snow is quite low -- about an order of magnitude lower than in the low-altitude Arctic. This is because of the high elevation of the central GrIS, with pollutants mostly confined to lower altitudes.

To date, the amount of black carbon in the region of the GrIS that is losing mass, known as the ablation zone, has not been quantified. Measurements here are complicated by complex terrain and by the difficulty of separating black carbon from other particles (e.g. dust) in the snow. While some scientists have hypothesized that dust may be darkening the ablation zone in southwest Greenland in particular, nobody has quantified the relative roles of black carbon, dust and other darkening agents in these regions.

Additionally, insoluble impurities concentrate at the surface when snow melts, since meltwater percolates down through the snowpack more efficiently than do particulates (e.g. Doherty et al. 2013). This further lowers the albedo and enhances melting, leading to more consolidation (Flanner et al., 2007).

This positive feedback gives rise to high concentrations of impurities in the ablation zones in particular. Because of this feedback loop, in a snowpack that has partially melted, it is not possible to distinguish whether elevated impurity concentrations *caused* enhanced melting or *resulted* from enhanced melting (or both).

### **Life on snow and ice**

Organisms on the ice sheet's surface also reduce the ice's albedo. Green, pink, purple, brown and black pigmented algae can grow in melting snow and ice. On ice, a mixture of dust, pebbles, soot and microbes called "[cryoconite](#)" also absorbs sunlight. Furthermore, microbes can bind to particulates like black carbon, retaining them at the surface in higher concentrations than in the parent snow and ice.

As with black carbon, nobody has quantified the magnitude of this source of darkening. As the climate warms and melt seasons lengthen, biological habitats will expand, and their contribution to darkening will likely increase (Benning et al., 2014).

### **Naked ice and water pools**

The exposure of bare ice and development of surface meltwater pools also reduces surface albedo, primarily in the near-infrared but also at visible wavelengths. The total albedo of clean glacier ice is around 60%, compared to 72% for clean melting snow.

Ice albedo decreases further, to between 20% and 50%, when it has high concentrations of impurities, as is common in the ablation zone. The albedo of melt pools is even lower, typically reaching values of 20% to 30%.

Low albedo due to bare ice exposure has likely contributed to recent extreme melting events on the ice sheet (Tedesco et al., 2013). Meltwater lakes on the ice sheet's margin have also expanded substantially inland to higher elevations with warming, decreasing albedo over sizable areas of the ice sheet (Howat et al., 2013).

## **Recommendations**

To determine exactly what causes the GrIS albedo to change, the scientific community must first quantify the contributions made by all of the processes described above. Currently, no such assessment exists. Instead, black carbon's role in reducing visible albedo has attracted most of the attention. We need to communicate the other important processes involved in albedo reduction to both scientists and the general public.

Remote-sensing data can provide large-scale information on processes occurring on the ice sheet surface, at high temporal resolution. But measuring and attributing albedo variations by means of satellite retrievals is challenging (Warren, 2013) because of the relatively low concentration of impurities on the surface of the GrIS and the relatively coarse spatial and radiometric resolutions, among other things. We therefore need airborne campaigns or improved spaceborne sensors to collect finer spectral and spatial remote sensing datasets.

We also need *in-situ* measurements in the GrIS's ablation zone that can distinguish the relative contributions of different impurity types (e.g., black carbon, dust, algae) to

albedo reduction as well as models that accurately simulate the GrIS surface energy balance and mass balance. For example, regional climate models need to refine the modeling of snow grain size and exposure of bare ice, and to include impurities and biological activity in their albedo schemes.

### **A critical understanding**

Given the role of warming in albedo change, and the projections of increased warming and enhanced melting, future changes in the GrIS albedo will likely result largely from warming and associated feedbacks. We need to quantify and understand these feedbacks, so that we can assess the energy budget at the ice-sheet surface and predict future changes in ice mass.

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#### **Caption for 5807**

Aerial photograph collected on July 24<sup>th</sup> 2015 from a digital camera mounted under a helicopter flying over the southwest portion of the Greenland ice sheet, nearby Kangerlussuaq. The meltwater stream divides two regions with the left area characterized by ‘dirty’ ice, covered by cryoconite and impurities, and the right area showing metamorphosed snow with a relatively low amount of impurities concentration. Because of the reduction in albedo due to grain size metamorphism, it is possible that the ‘clean’ portion might actually absorb more solar radiation than the ‘dirty’ side. The meltwater streams, the impurities on the ice surface and the metamorphosed snow/firn all contribute to the suite of processes driving the changes on albedo.

#### **Caption for 5704**

Aerial photograph collected on July 24<sup>th</sup> 2015 from a digital camera mounted under a helicopter flying over the southwest portion of the Greenland ice sheet, nearby Kangerlussuaq. The images can be divided into three sections, each covered by a different surface feature: on the left, meltwater of the shore of a supraglacial lake exhibits its outstanding and peculiar turquoise color; in the middle, bare ice where impurities have



been removed by the previous presence of the lake; on the right, ice and snow covered by surface impurities. The meltwater streams, the impurities on the ice surface and the metamorphosed snow/firn all contribute to the suite of processes driving the changes on albedo.

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